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A Modular and Flexible Design of Hyperconnected Assembly Factory

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Abstract: *Modern assembly factories increasingly encounter the challenges posed by highly diversified products and fluctuating market demand. Hyperconnected mobile production, which organizes the core production equipment in standard production modules and allows them to be shared among multiple participants in the Physical Internet, is a solution in response to these challenges. In this paper, we adapt the hyperconnected mobile production concept to the assembly industry and introduce a fractal layout design. In our design, a fractal center is a standard assembly module with a predetermined throughput rate and is equipped to assemble all variants of products. All assembly tasks of an individual product, from subassembly to finishing, are performed in one fractal center. In addition, fractal centers employ mobile material handling and assembly equipment and operators that do not have to continuously occupy fixed locations. We illustrate the shareability, scalability, reconfigurability, and adaptability of the proposed hyperconnected modular design and present a design framework for fractal centers.*

Keywords: *Physical Internet, Hyperconnected Production, Flexible Assembly, Scalability, Adaptivity, Reconfigurability, Shareability.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☒ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☐ PI Networks, ☐ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

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1 Introduction

Assembly is a type of manufacturing that combines components into final products. It is widely used for producing a variety of product types, including electronics, furniture, robots, machines, vehicles, ships, aircraft, and buildings. Typically, to improve production efficiency and ease the training of workers, the assembly work of products will be allocated to a set of workstations, and workstations are linked by specific product flows that are normally irreversible. The product and material flows among workstations are synchronized by a certain amount of time called “takt time”. Takt time is defined as the time interval between two consecutive launches of production. For example, at the beginning of a takt time, workers at each station start to assemble products until the end of the takt time, then workers move the completed products to the next stations, come back to the original workstation, and repeat the same or similar assembly work in the next takt time.

Nowadays, product diversification and uncertain demand are major issues in the assembly industry, which may cause low resource utilization and excessive inventory. Furthermore, to improve customer satisfaction and gain competitiveness, assembly businesses need to shorten the product delivery time as well as maintain the production cost per product at an economic level when the throughput increases or decreases. Additionally, environmental issues, such as carbon emissions from product transportation, motivate business owners to rethink and improve their delivery system.

Modular and flexible layout design is one solution. Modular layout design refers to the design of stations and product flows in factories using standard patterns, to decrease the learning time and increase efficiency. Fractal layout organization applies the modular layout design concept and organizes equipment and workstations into “mini-factories within a factory”. In such an organization, all core production activities of one product are performed within one modular production center, or Fractal Center (FC), so that each FC functions like a “mini-factory” and operates almost all production processes independently from other FCs.

The flexible layout design indicates stations and equipment are able to be reconfigured quickly and with a low cost when products or demand changes. The emerging robotic and information technologies support progress in flexible layout design. For example, the “Plug-and-produce” concept embedded in manufacturing equipment can produce multiple variants and be reconfigured swiftly. Relying on such flexibility technologies, the concept of movable factory design has been proposed. A movable factory can be quickly uninstalled, encapsulated, transported, installed, set up, and easily reconfigured for different product variants or other factors. Extended from the movable facility concept, the mobile supply chain is proposed to relocate the facilities and optimize the performance of the overall supply chain.

Hyperconnected production, leveraging the Physical Internet (PI) principles and hyperconnectivity introduced by Montreuil et al. (2013) and Sternberg and Norrman (2017), proposes to realize on-demand production through the open certified production facilities and targets to improve the resource utilization rate as well as economic, environmental, and societal efficiency and sustainability by an order of magnitude. The material supplying and product shipping among those facilities are encapsulated in standard containers in the hyperconnected network. Extended from the hyperconnected production and movable factory concepts, hyperconnected mobile production utilizes “plug-and-play” enabled equipment to allow the dynamic relocation of production capacity.

Most of the literature regarding fractal layout organization focuses on the performance of intra-facility logistics. In fact, the use of mini-factories could also enhance the shareability among multiple facilities, because activating or deactivating one FC has less impact on others.

In this paper, we exploit the concepts of fractal layout organization and hyperconnected production for assembly factory design and propose a modular and flexible design for hyperconnected assembly factories. Such a hyperconnected assembly factory has two types of centers: (1) intra-facility network coupling centers, such as receiving centers and outbound shipping centers; and (2) fractal assembly centers, which contain all core equipment and workstations in the facility. For simplicity, in this paper, we assume that each type of equipment and workstation appears in each fractal center to ensure that each center can assemble any variant of products. Furthermore, we utilize movable equipment and operators for material handling with no fixed material handling equipment to enhance flexibility.

Equipped with the concepts of PI and hyperconnectivity, our research further allows for sharing equipment and workstations in the open certified facility network, and such sharing could be enabled by adding, removing, or reassigning FCs from one user to another. It could allow assembly factories to efficiently scale their production capacity up or down by activating or deactivating fractal centers as necessary. The drawbacks of such a distributed production design may be higher cost and lower equipment utilization when the demand is rarely changed and the product variants are minorly altered.

Figure 1 illustrates an example of how fractal centers are shared among hyperconnected production factories. When customer demand changes in certain regions in period T+1, a hyperconnected assembly factory allows its FCs to be shared with other PI-certified facilities instead of fixing FCs in factories and sending final assembly products over a long distance. Such FC sharing could occur within the same company, or between competitors for horizontal collaboration (e.g., company 1 and 2), or between a company and its supplier for vertical collaboration (e.g., company 1 and its supplier).

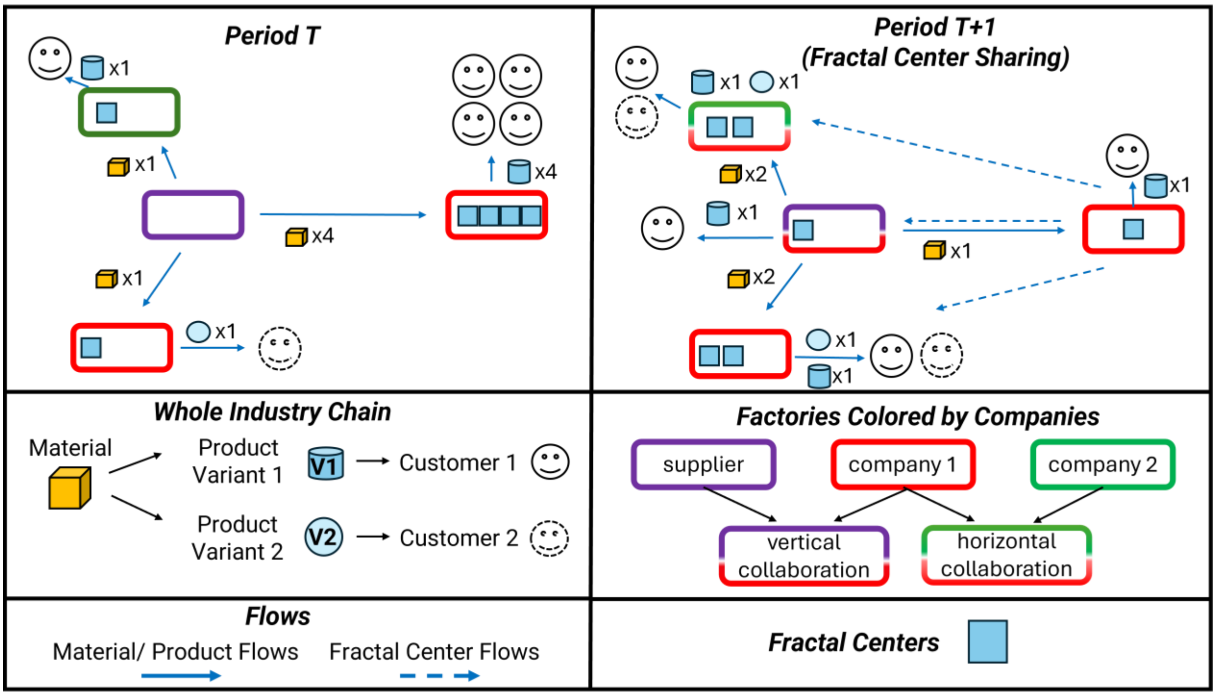

Figure 1 Illustrating the Shareability of Hyperconnected Production Factories with Fractal Centers

This paper is organized as follows: in Section Two, we present a review of related literature; in Section Three, we provide a use case that the proposed hyperconnected assembly factory design can be applied; in Section Four, we provide the details of the design assumptions and framework for assembly fractal centers; and in Section Five, we summarize the key aspects of the hyperconnected assembly factory design with fractal layout organization and outline avenues for future research.

2 Literature Review

This section provides a detailed literature review on flexible production, fractal layout organization, and hyperconnected production.

Flexible Production

Flexibility refers to the ability of the production system to adapt to product variants or demand changes. One key aspect is to organize the layout of machines and workstations in a way that material and product flows are easier to adjust, such as cellular production (Rajagopalan & Batra, 1975) and matrix production (Schmidtke et al., 2021). Another important aspect is to use equipment and tools that can be efficiently reconfigured, such as agile production robots (Jin et al., 2023; Nilsson et al., 2023), flexible conveyors (Bulgakov et al., 2022) or auto-guided vehicles (Vlachos et al., 2022).

The development of flexible production technologies promotes the concept of movable factories. Kazemi et al. (2023) reviewed the related literature. They summarized some advantages of the movable factories and listed numerous applications in industries, such as reducing the transportation effort for heavy and fragile final products (for example, wind turbine tower sections assembly), improving responsiveness to customers for shorter delivery time, decreasing the carbon footprint, and minimizing the storage space for Just-In-Time assembly and delivery (for example, prefabricated construction). Alarcon-Gerbier and Buscher (2022) presented a systematic review of the facility routing and locating methodologies for modular and movable facilities, and enumerated some potential areas and requirements for implementing a mobile supply chain.

Fractal Layout Design

Venkatadri et al. (1997) developed a design methodology jointly assigning products to fractal centers and the layout of fractal centers for the job shop environment. Montreuil (1999) introduced a new concept of fractal layout organization where the total number of major workstations is allocated equally across several fractal centers. Saad and Lassila (2004) investigated various fractal center configuration techniques with different objectives and constraints. Shih and Gonçalves Filho (2014) discussed a fractal center layout principle and implemented it in a Tabu search heuristic.

Hyperconnected Production

Hyperconnected production (Marcotte & Montreuil, 2016; Montreuil, 2016) not only focuses on equipment re-deployment among facilities of one company, but also enables equipment sharing among either competitors at the same stage in the supply chain horizontally, or businesses at up- and down-stream stages vertically. In such a way, on the one side products can be further realized through a hyperconnected supply chain with fewer business-dedication restrictions, on the other side businesses could efficiently and agilely scale up or down their facilities as needed.

Such design relies on open and readily available facilities in the PI network with standard production principles, to guarantee both technical and economic feasibility. Additionally, hyperconnected production requires core equipment leveraging the start-of-the-art flexible manufacturing technology to reduce the effort on installment and removal, thus bringing higher agility.

3 Use Case

We consider a use case in which the products are large and heavy items with variants having similar production requirements. Here, the similarity of variants is measured by their process types required (bolting, screwing, welding, etc.), precedence diagrams, and task durations. Second, transportation and storage of materials require much less time and cost than in-process or finished products. In this way, relocating factories would become more beneficial than fixing factories and delivering products. Third, customers are geographically dispersed, and demand fluctuates over time. Fourth, core equipment is “plug and produce” enabled. In our context, the core equipment is measured by its necessity in the given assembly process and its cost. For instance, if certain pre-processing equipment is not costly and can be replaced by other alternatives, then it could be classified outside of the fractal center and each local facility could select the equipment by their own decision. Fifth, all business participants are PI-certified. This allows equipment sharing to be as seamless and efficient as possible.

4 Proposed Hyperconnected Assembly Factory Design

This section aims to illustrate how the proposed hyperconnected assembly factory design can be applied to the use case.

Assumptions for Fractal Center Design

A hyperconnected assembly factory is composed of network coupling centers and fractal assembly centers. After arrival at the factory, materials are unloaded and temporarily stored in the inventory area, which serves all FCs. According to the assembly schedule, materials are sent to assigned fractal centers for further processing. When products are completed, they will be transported to the global outbound staging area and ready to depart. Some assembly methods may require utilities, for example, electricity, waste removal, or cooling water for heat dissipation. Flexible pipes or tubes that are easy to reconfigure and set up may be needed in such cases.

All FCs are designed to have the same workstations, product flows among workstations, and the same pre-determined takt time. The "same takt time" assumption simplifies the FC allocation and transportation modeling. When the overall throughput of the factory needs to be adjusted, we could adjust the number of FCs instead of redesigning them to achieve the desired throughput rate.

Figure 2 exemplifies a hyperconnected assembly factory with fractal layout organization where the receiving and inventory area is global to the overall factory. Note that material workers can globally serve multiple fractal centers, and different fractal centers may have different starting times, for example, to avoid surges in logistics traffic. Fractal centers have a constant throughput of x units per day, and the factory throughput is a multiple of x.

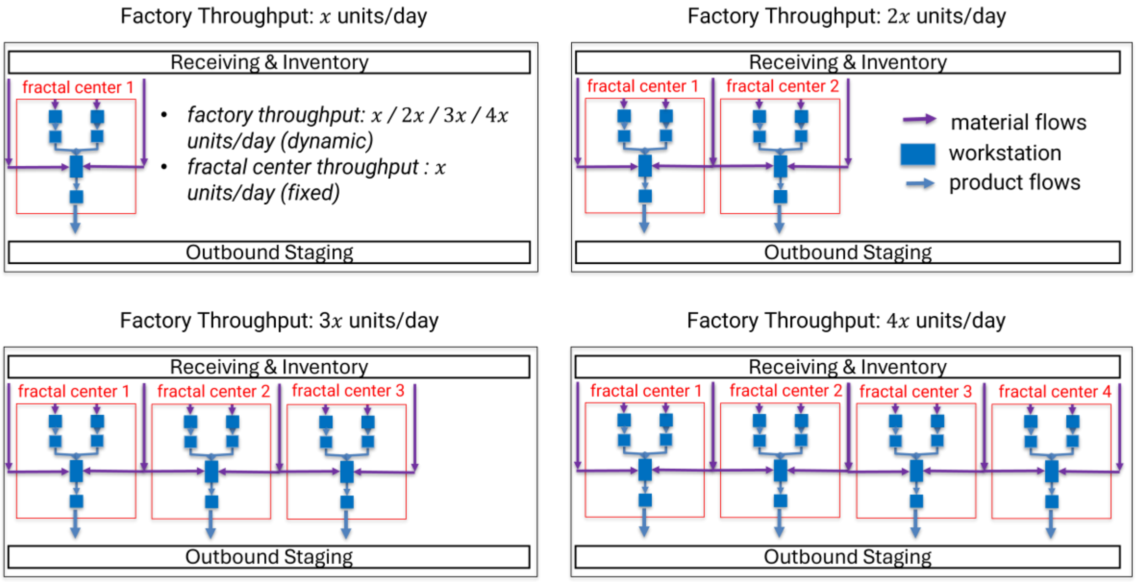

Figure 2 Example of Product and Material Flows in A Hyperconnected Assembly Factory with Changing Throughput

Fractal centers are adjustable to all variants of products cost-efficiently within a short time. This poses a high requirement on the machines and equipment and relies on the similarity of the product variants. Jin et al. (2023) studied a control method for flexible robots in a fully automation manner with pre-defined task execution information and implemented a test production for three types of Tetris-like puzzles. Nilsson et al. (2023) built a "plug-and-produce" and configurable multi-agent system for flexible manufacturing robots and conducted the production for structural components of wooden houses with modification on part design. More feasibility and viability tests of this assumption need to be conducted for other products.

Note that although fractal centers share the same fraction of each type of equipment, workers could be different. Some fractal centers could be staffed to assemble more labor-intensive product variants, while others may be less staffed to improve the utilization. Furthermore, because of the mobility, workers may be allowed to travel across fractal centers and work in multiple centers. For example, highly skilled workers could travel to work on rare and difficult tasks in different centers.

Design Framework

The proposed design framework incorporates nine interactive models. The structure of models for fractal center design is detailed in figure 3. The design process starts from the demand model to the performance analysis model, with feedback loops to the previous model and the beginning demand and project model.

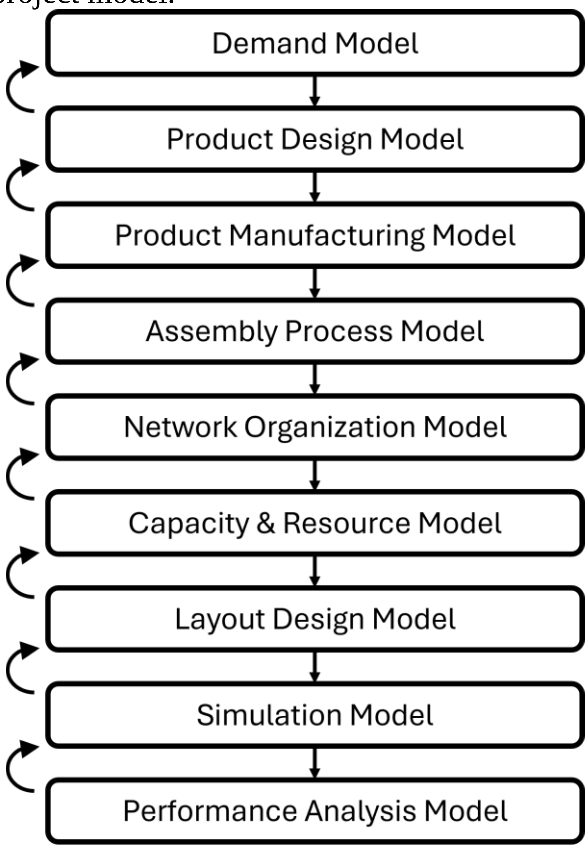

Figure 3 Design Models for Fractal Center

The demand model decides the throughput rate of fractal centers, considering the market demand, inventory, production and logistic efficiency, and disruption risks. The product design model outputs the multi-tiered structure of products that need to be assembled in fractal centers, which includes the details from components to the final products. Given the inputs about product design and the manufacturing technology alternatives, the product manufacturing model determines what manufacturing processes and manufacturing equipment are required in fractal centers, and generates the manufacturing bill of material. For instance, computer-aided product manufacturing information (PMI) can be leveraged to promote automation of assembly and inspection requirements, material specifications, and other definitive digital data. The assembly process model defines precedence diagrams for all product variants and executable assembly instructions given the inputs from the previous models. The network organization model outputs product flows in fractal centers according to the results from previous models. Common example organizations are integrated serial lines, job shops, product-oriented lines. The capacity and resources model comprehensively decides the number of workers (can be human workers or robots), the type and quantity of equipment, machines, and tools, as well as the assignment on how to use them. Assembly balancing, material handling, and worker scheduling are common decision processes involved in this model. The Layout design model executes the detailed facility layout via predefined modularized resources. The model in a hyperconnected assembly factory impacts the need for rapid and cost-saving design processes and increases the tendency to apply the fractal concept of mobile production in the manufacturing environment. The simulation model is used to aid in the production process design, process planning, operations validation, and performance assessment. In the design phase, while building the model and running the experiment, improvement opportunities were identified in the production process, which led to changes in the manufacturing process. The performance analysis model examines the performances of previous models, assesses the assumptions of models, and identifies improvements for the next round of design.

The proposed fractal layout design for hyperconnected assembly factories is based on the following assumptions:

1. The design process starts from the demand analysis and assumes the fractal center takt time is fixed. The capacity and resource model employs takt time driven processes for assembly balancing and material handling processes. Simulation model and performance analysis model need to track and analyze the intra- and inter-facility operations.
2. Product and process are designed specifically to support modular and flexible production. For instance, “plug-and-produce” production and material handling equipment could be considered in the product manufacturing model. Products should be designed for easier and more secure material handling, for example, having some handles, grips or knobs that are easier for mobile gantries or AGVs to lift, transport, drop, and store.
3. Kitting is selected as the main part feeding mode for most parts to alleviate the logistic workload of the assembly for multiple product variants. The kit storage is dedicated to fractal centers for management simplicity.
4. Logistics and layout interaction should be considered among fractal centers. Although all production processes in one FC are independent of other FCs, the logistics and layout of FCs may interact with each other. For example, logistics workers can feed kits and consumable parts to stations in multiple FCs in one travel.

Figure 4 shows the high-level core foundation of the model used to create the layout. It identifies how different pieces come together to become a layout, and all the decision-making is done using standard tasks and rules. The layout design model simplifies the complicated process and reduces redesigning effort by standardizing the underlying rules. In fact, it is used to integrate design and engineering concepts more efficiently by employing reusable solutions. Such a model can also translate human interpretation into computer language to be reusable for modular facility design with dynamically changing products.

This model applies a substantial foundation for automated dynamic layout design, which needs a deep understanding of the production process, resource flows, and physical arrangement of the resources.

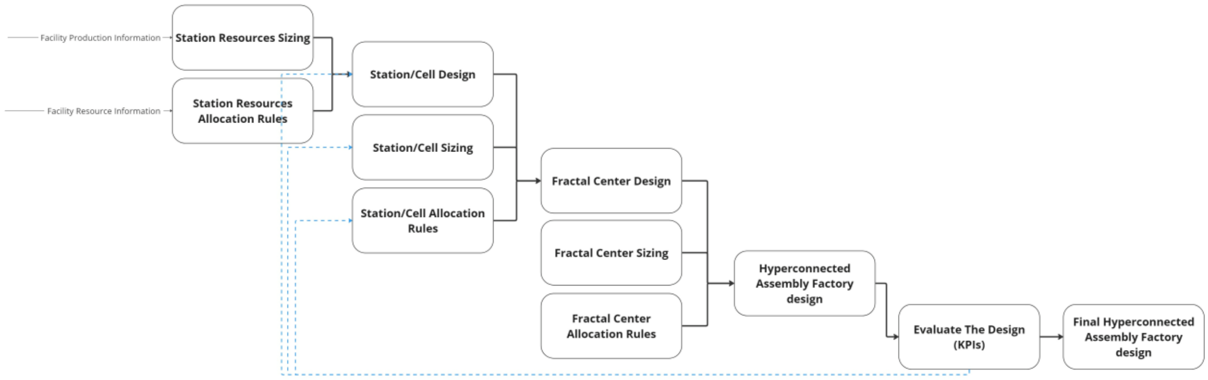

Figure 4 Fractal Center Layout Design Steps

Characteristics

Dynamic activation and deactivation of fractal centers enhances scalability. Mimicking the digital network, the standard fractal centers in the PI facility network act in the "plug-and-produce" mode with standard protocols. In a whole industry chain, companies at the same stage could share or combine their standard production modules at an economic scale, business at different stages could also share the equipment, like outsourcing or subcontracting, to realize an efficient mobile production with necessary governance and certification according to the PI regulations.

Reconfigurability is achieved by mobile equipment and operators. Reconfigurability refers to the ability to re-deploy equipment within FCs quickly and inexpensively. Mobile equipment and operators do not have to continuously occupy a fixed floor space enabling the movement of equipment during reconfiguring.

Adaptability measures the ability to change the equipment and adjust the configuration to adapt to product changes, including the change of the mix of product variants and the change of product design. Sharing the same proportion of equipment enables every fractal center to produce any product variant, saving the effort of adapting to changing product mix. Furthermore, for innovative projects, the validation test can be conducted on one fractal center. If the test succeeds, other fractal centers can be adjusted accordingly thanks to the similarity of product flows. This saves the testing time and enhances the agility of the factory.

Still, the proposed hyperconnected assembly factory design may incur duplicated equipment and bring more risks during FC sharing. Thus, more management effort on dynamic coordination and collaboration is required to operate the hyperconnected assembly factory network.

5 Conclusion and Future Design

In this paper we develop a modular and flexible design for hyperconnected assembly factories and provide a design methodology for the fractal centers, the standard production modules that are shareable to participants in the PI network. The design relies on the PI principles, modular layout with independent product flows, plug-and-produce mode enabled equipment, and the pioneering flexible assembly system technology. It aims to promote global collaboration and optimization among PI facilities in the whole industry chain, improve the shareability, scalability, reconfigurability, and adaptability of assembly facilities, and ultimately magnify efficiency and sustainability from economic, environmental, and social perspectives. The shareability is improved by the PI-enabled hyperconnected assembly factory network. The scalability of factories is achieved by activating and deactivating fractal centers with independent product flows. The adaptability and reconfigurability are improved by plug-and-produce mode enabled flexible assembly system technology. The environmental sustainability could be enhanced by reducing product delivery distance and thus decreasing carbon footprint due to the relocation of FCs.

There are several opportunities for further research. We hereafter summarize four key threads. First, research on multi-standard fractal centers is needed. In a multi-standard fractal center design, FCs may have different workstations or the same number of workstations but different product flows. Note that in the multi-standard fractal center cases, every FC could still produce any variant of product, but is more efficient for a subset of products. For example, for automotive assembly factories, some types of FCs can be more suitable for sedans, whereas vans and trucks can be preferred in other types of FCs. What takt time and what equipment should be used in each type of FCs may depend on specific product and process attributes in such cases.

Second, rigorous comparison with other assembly factory designs is also essential. On the one side, the comparison should encompass a detailed assessment of fixed factories with dedicated equipment, fixed factories with shareable equipment, movable factories with dedicated equipment, and movable factories with shareable equipment. On the other side, other layout organizations should be investigated, such as serial line design, product-oriented design, and typical modular design allowing product flows across multiple production modules.

Third, powerful optimization and decision-making models are in need for coordinating and scheduling FC sharing in the hyperconnected assembly factory network. Some representative research problems include how many FCs should be active in each factory, when and how FCs should be transported to other facilities, and if workers should be allowed to work in different FCs.

Fourth, pilot tests are crucial to validate the technical and economic feasibility of the proposed hyperconnected assembly factory design, especially when FCs are shared among different businesses.

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